Studies of the Origins of the Kuroshio and Mindanao Currents with EM-APEX Floats and HPIES

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LONG-TERM GOALS

Improving observations and understanding of major oceanographic features, phenomena and dynamical processes, especially through the development and application of instruments based on the principles of motional induction.

OBJECTIVES

The primary objectives of this observational program are to determine bifurcation of the NEC into the Kuroshio and Mindanao currents, and determine the Kuroshio volume transport off NE Luzon Is. The installations of HPIES in OKMC provided the first opportunity to compare the HPIES measurements with the velocity and density observations from moorings and Seagliders.

APPROACH

We used two APL-UW developments: HPIES and EM-APEX to observe and quantify flow in the Western Philippine Sea.

HPIES is an abbreviation of Horizontal electric field, bottom Pressure and Inverted Echo Sounder. The HEF measures the vertically-averaged, conductivity-weighted barotropic horizontal velocity. The pressure and IES data determine baroclinic velocity when operated in a horizontal array and provide the conductivity weighting correction for HEF. The use of bottom-mounted horizontal electric field sensors combined with inverted echo sounder units (HPIES) complements the ADCP moorings and Seaglider profiles in the Kuroshio near the NE tip of Luzon, PH. The shipboard CTD and Seaglider data provide the information to construct a GEM model for interpreting the IES observations and providing the conductivity–velocity correlations for HEF interpretations.

To observe the vertical structures of the NEC (N. Equatorial Current) as it flows toward Luzon, EM-APEX floats were deployed in the Western Philippine Sea. These floats observed the T, S and V in the upper 800 m with pair profiles separated by half an inertial period, which provided estimates of the mean and inertial velocity components.

WORK COMPLETED

Nine EM-APEX float were deployed along 135°E between 13°N and 22°N in June 2012 by KORDI staff on the R/V *Onnuri* (Fig. 1). The cooperation of Jeon Dongchull, Eung Kim and Park Jae-Hun was vital for the success of this deployment. All the floats profiled twice, half an inertial period apart, to 800 m. Then the floats drifted at a holding depth (~200 m) for mostly 10 d that moves with the NEC.

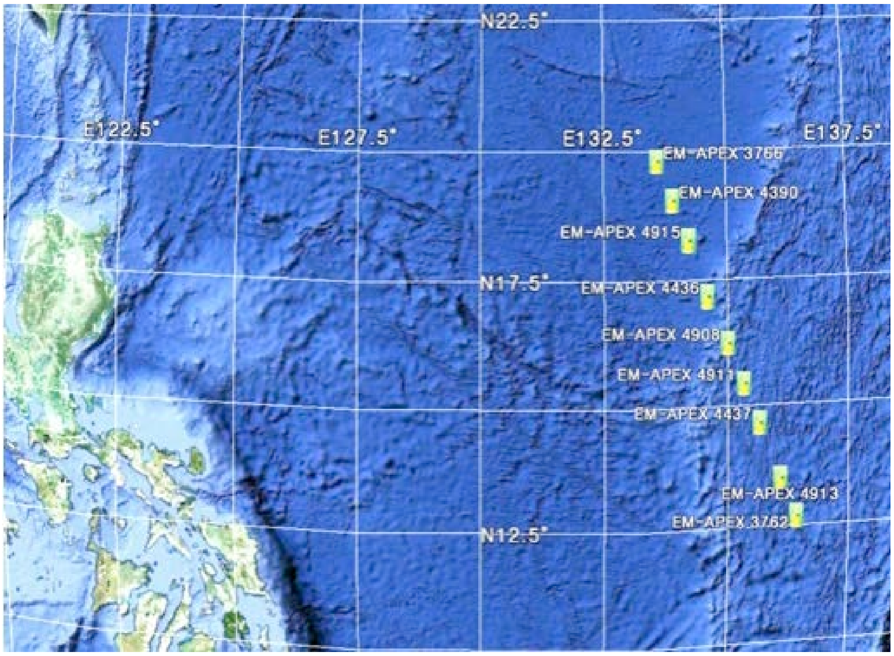

Fig. 1: Deployment positions for the 9 EM-APEX floats deployed by the Korean Ocean Research and Development Institute's R/V* Onnuri *in June 2012 between 20°N and 12.5°N.

R/V *Revelle* cruises 1205 in June 2012 and 1307 in June 2013 were devoted to the deployments and recoveries of ADCP moorings, HPIES and CTD stations along 18.8°N, NE of Luzon Is., respectively. The field operations went well and all gear was recovered.

Six upper-ocean ADCP moorings (R.-C. Lien) were deployed around five bottomed HPIES (Fig. 2). The ADCPs were moored at 600-m and upward looking. The HPIES provided the depth-averaged velocity based on the electric field generated by motional induction. Thus, the combination provides both upper-ocean Kuroshio transport and total-water transport. The moorings and the HPIES are installed NE of Luzon. The HPIES and ADCP array are centered at the Kuroshio stream.

Much of the past year has been devoted to quality control of the HPIES data and comparisons of HPIES observations with other methods used in the area. Suitable co-located and simultaneous observations include shipboard ADCP, Lien's ADCP moorings, Lee's Seagliders and single EM-APEX floats that pass over the array. In this work we have been aided by the data, analyses and advice of Ren-Chieh Lien, Craig Lee and Barry Ma and the GEM model of Vigan Mensah (NTU) and Magdalena Andres (WHOI) used to compute sections of the hydrographic structure based on the IES array.

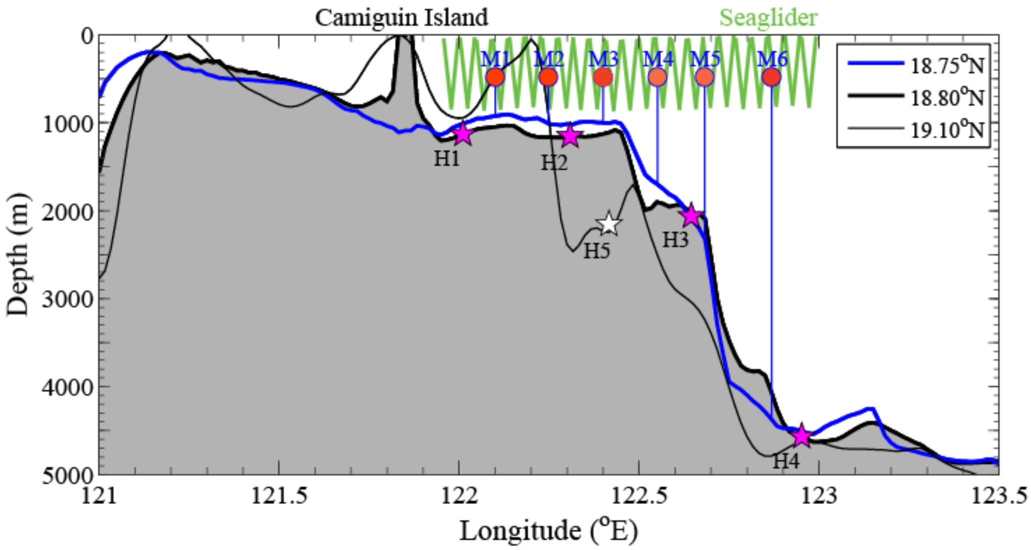

Figure 2. Bathymetry across HPIES, mooring and Seaglider lines. H1–H4 span across 18.80°N (thick black line), and the lone H5 is at 19.1°N (thin black line). Lien's ADCP moorings (M1–M6: blue lines and red dots) are along 18.75° and Lee's Seagliders (green paths) are on 18.75°N.

Initially, it appeared that some of the HEF (horizontal electric field) instruments on the HPIES had failed. The evidence was that several of the HEF units exhibited failure to pinch the water switch tubing properly. After analysis, it was found that the default mode of the water switch provided adequate pinching for about 80% of the time. So we have proceeded with analyses of the HEF data. In addition, the calibration system that operated every few days was used to correct observations.

RESULTS

The array of EM-APEX floats (Fig. 1) was successful in revealing the jet-like, banded NEC flow toward a bifurcation region south of Luzon Bay on Luzon Is. The floats revealed the zonal bands of flow in both the EM velocity field and the geostrophic flow. Qiu et al. (2013) reported similar results.

Figure 3 plots the float trajectories as they drifted toward Luzon Is. There is a nice show of floats appearing to converge in a jet-like flow. Float 4437 entered the Kuroshio but passed through the Luzon Strait and entered the South China Sea, getting trapped in the mesoscale eddy SW of Taiwan. Float 4911 moved steadily toward Luzon where it stalled, providing a longitudinal section of the NEC. Floats 4915 and 3763 were entrained into the Mindanao Current or Kuroshio and rapidly moved south or headed toward Taiwan and beyond, respectively.

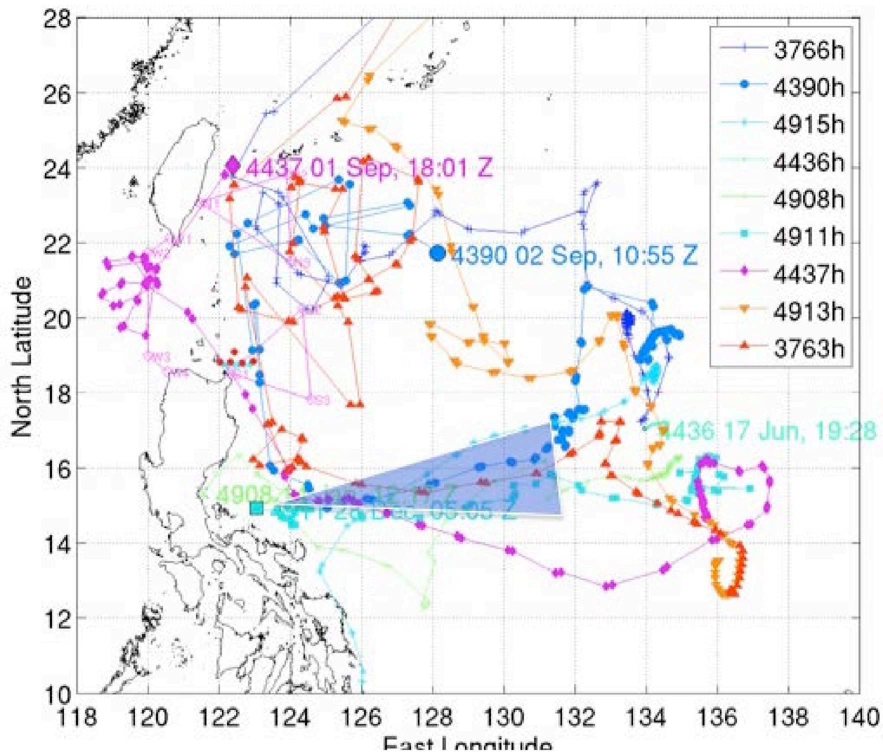

Fig. 3: Float trajectories from deployment along 135°E. Some floats went directly toward Luzon Is. Others tended to go NW toward Taiwan. Floats that neared Luzon, went mostly N.

Initially, the floats deployed along 135°E (Fig. 1) profiled rapidly. Figure 4 displays the longitudinal velocity sections, both geostrophic and EM based, showing the jet-like structure of the NEC. Qiu et al. (2013) reported similar jets. Subsequently, the floats were allowed to drift westward (Fig. 3) with profiling every 10 days.

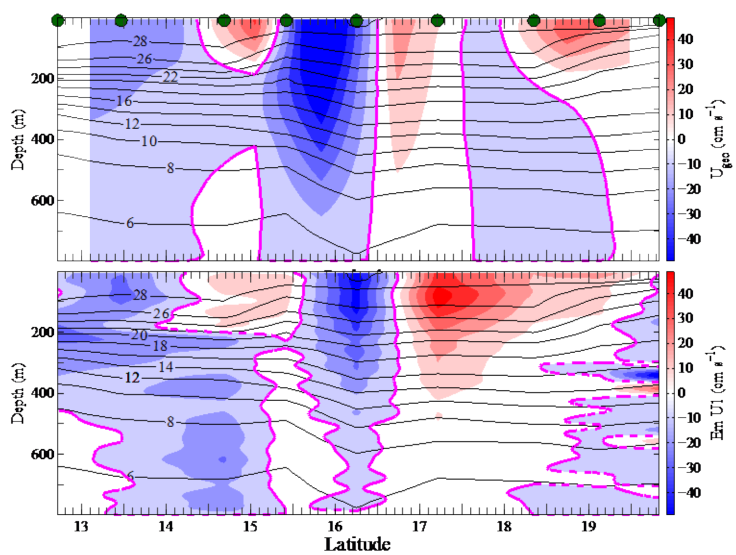

Fig. 4: 1st two days of all 9 EM-APEX profiles to 800 dbar along 135°E in June 2012 between 20°N and 12.5°N in the region of the NEC as in Fig. 1. Upper panel is the geostrophic velocity section and the lower panel is the corresponding EM section.

Float 4915 joined the Mindanao Current and moved rapidly south, ending in the Celebes Sea before being trapped in an eddy and dying. Float 3763 was entrained into the Kuroshio and went to the NNE. These floats provided a latitudinal section along the Mindanao and Kuroshio currents. Figure 5 shows the water properties and along track absolute velocity versus latitude. The bifurcations latitude is clearly shown to be around 15°N.

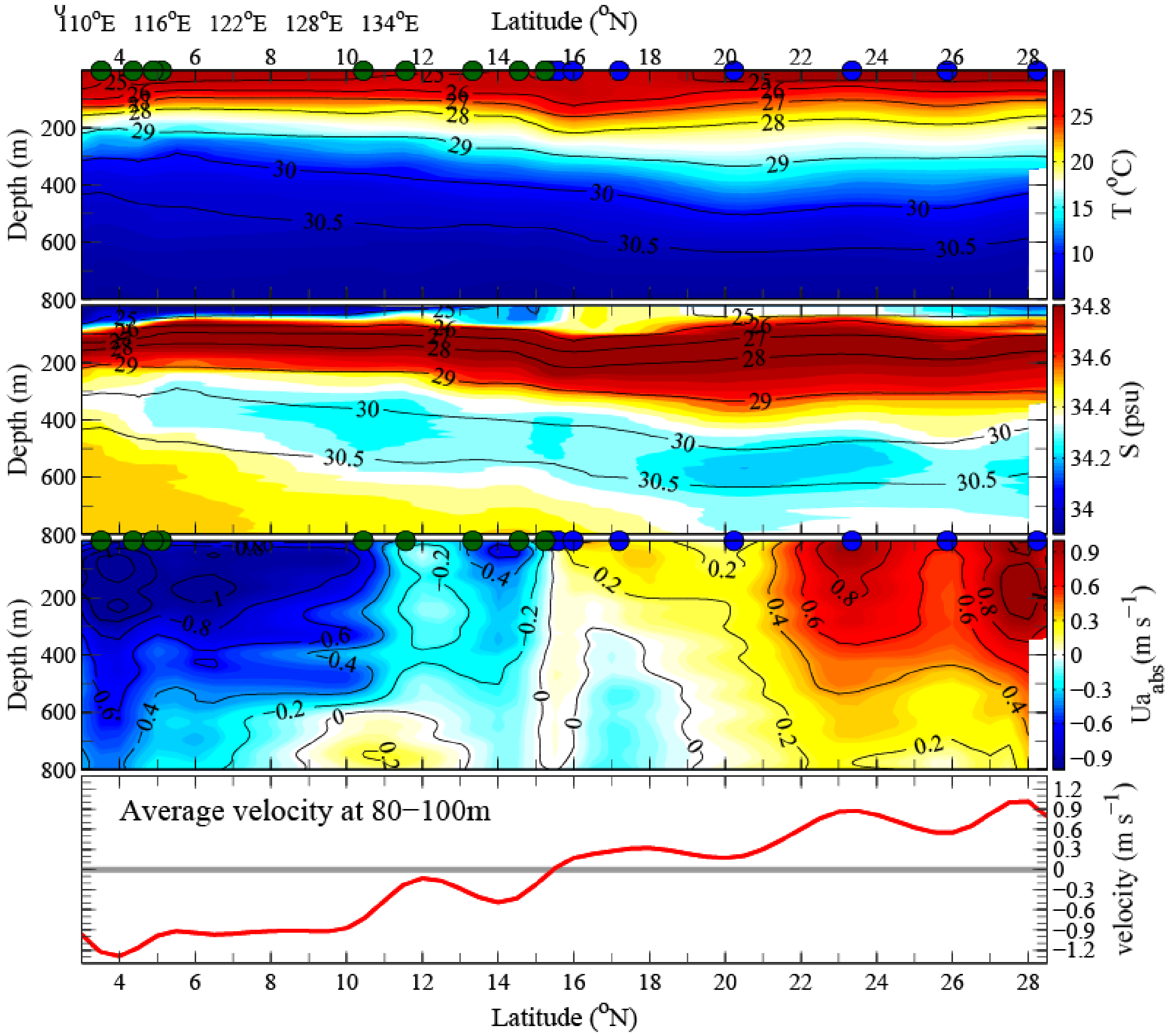

Fig. 5. Two EM-APEX floats entered the bifurcation site at 15°N. One flowed north (blue dots: float 3763) joining the Kuroshio Current, and one flowed south (green dots: float 4915) joining the Mindanao Current. Along these tracks temperature, salinity, absolute velocity and average velocity at 80–100 m are shown as a function of latitude. The oscillations of float velocities are probably the result of flow and eddy interactions.

Results from the floats include comparisons of geostrophic vs. EM-derived velocity profiles, velocity and water mass structures along the tracks of floats that ended up in the Kuroshio and Mindanao currents and relationships between AVISO surface current and float profiles.

One ongoing study is to compare parameterizations of turbulence based strain with one using both shear and strain.

Pressure Data

The raw pressure data from HPIE is binned and averaged into 10-minute interval pre-processed data. Then the data are first band-passed to the diurnal (18–34 h) and semidiurnal (6–18 h) frequencies. Seven-day running windows are used for the spectral analysis. A new time series of the spectral peaks at the diurnal and semidiurnal frequencies are reconstructed. A sanity check using the model output of surface elevation from the OSU TOPEX/Poseidon Global Inverse Solution (TPXO)[1] is conducted. The TPXO data are processed as the PIES pressure data for comparison. Figure 6 shows the time series and scatter plots of PIES pressure and TPXO elevation. The plots show the PIES pressure data is in good agreement with the model.

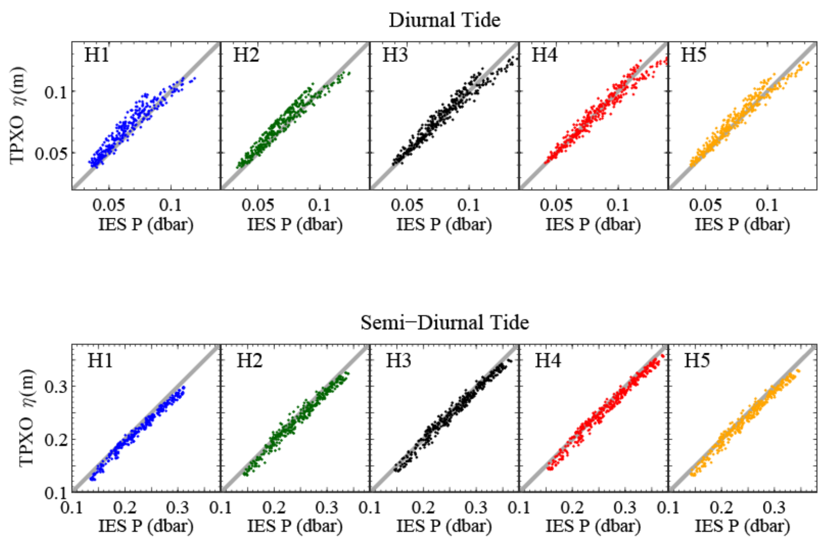

Figure 6. Scatter plots of the TPXO surface elevation vs. PIES pressure.

Travel Time and Gravest Empirical Mode

The travel time (τ) is first binned and averaged into 10-minute intervals. Then the measured τ is converted to τ_{800} (travel time equivalent to 800 dbar, Fig. 7) using the sound speed derived from the hydrographic profiles. H3 data exhibited errors due to instrument problems. H5 data further downstream on the Kuroshio center axis is used as a replacement for H3. The Gravest Empirical Mode (GEM), built from a database of hydrographic data previously acquired in the vicinity, provides lookup tables enabling the τ_{800} data to be converted into full depth hydrographic profiles. In this application, the GEM lookup tables are built using the Seaglider profiles, historical CTD and the CTD casts during the HPIES deployment cruises. The H3 travel time measurement is abnormal, thus the downstream H5 is used for replacing H3. The H5 is located downstream of H3 along 325°T. The Kuroshio Current direction is ~330°T at this location. Thus using the H5 data to replace H3 seems reasonable.

[1] OSU TPXO website http://volkov.oce.orst.edu/tides/

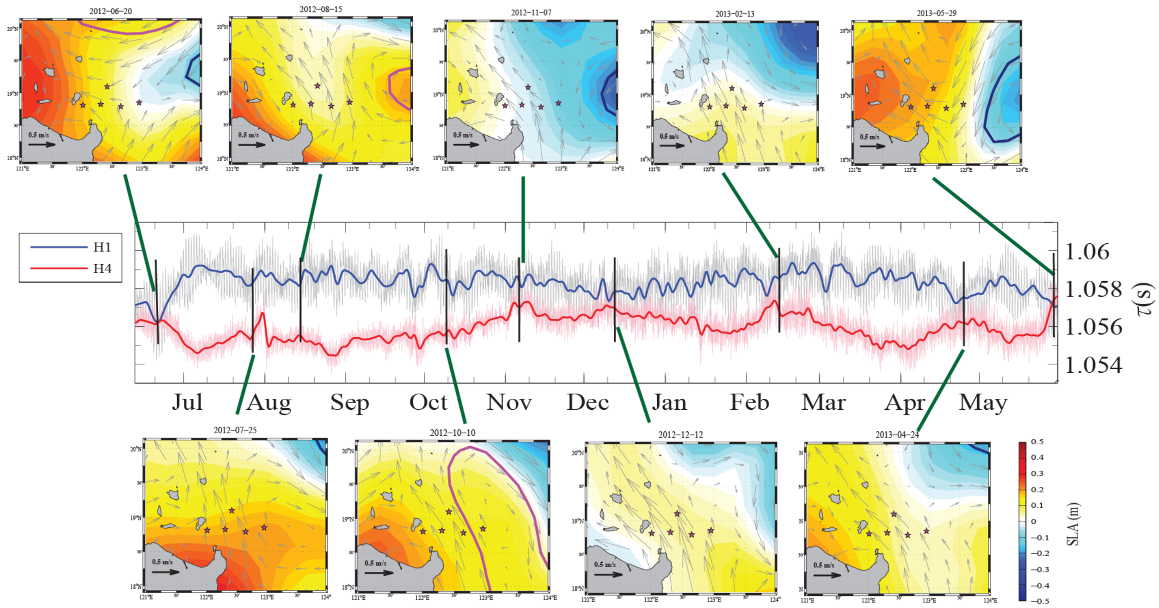

Figure 7: The travel times for the upper 800 m (τ_{800}) with snapshots of AVISO sea level anomalies, which exhibit the presence of eddies and sea level gradients. The observations confirm the influences of mesoscale eddies on the various velocity and transport estimates.

The travel times in Fig. 7 demonstrate that in June 2012 and June 2013, the baroclinic velocity over the section is nearly zero. Sections from moored ADCPs, shipboard CTD casts, and HPIESs exhibited similar low transport results.

Based on CTD casts and Seaglider transect, a GEM model was generated for the interpretation of travel times in terms of water properties (Meinen et al. 2002). The full description of GEM construction is described in a separate report (Mensah et al. 2014).

The PIES data present the advantage of providing full depth profiles of velocity. It is then possible to obtain valuable information on the current below the core of the Kuroshio. The monthly current velocity sections (Fig. 8) show that a southward flowing undercurrent with a strong temporal and spatial variability is present below ~400 m. A study of this undercurrent, based on Seaglider sections, is currently in progress (Ma et al. 2014). It is hoped that the PIES derived velocity profiles will be a complement to the Seaglider data and will provide valuable qualitative information about this undercurrent. Qu et al. (1997) and Hu (2012) report observations of the Kuroshio Undercurrent off Luzon.

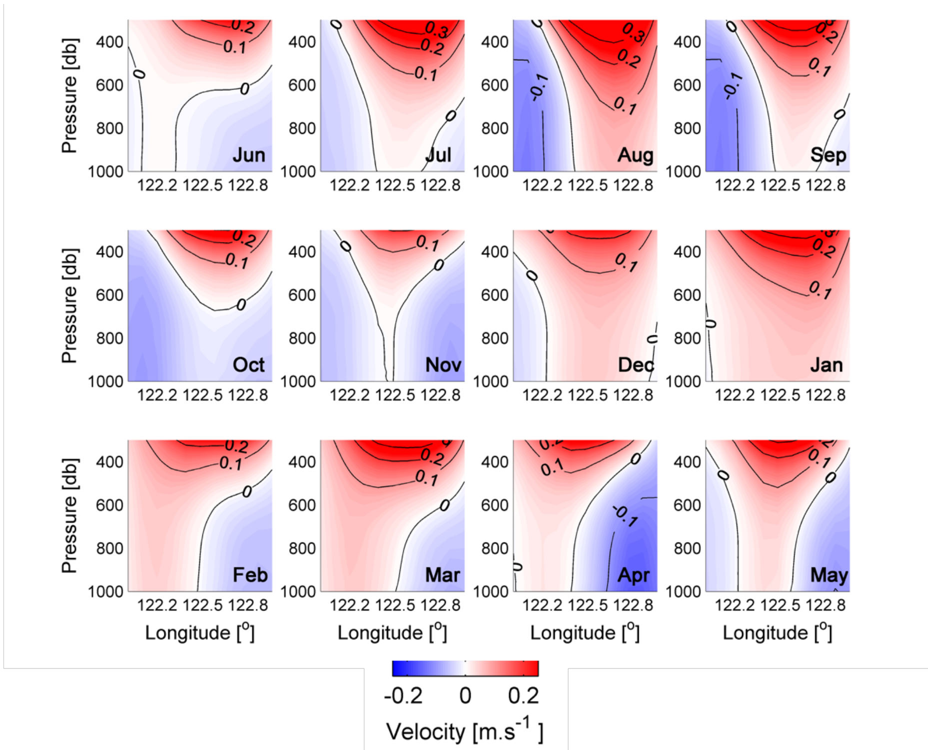

Figure 8: Monthly map of deep (>300 dbar) current across the HPIES-line. These current profiles based on IES and Seaglider could also be used to determine the structure of the level of no motion below the Kuroshio east of Luzon and its spatial and temporal variability. Note that evident depth variations of the level of no motion are evident.

HEF

The barotropic velocity derived from the HEF can be described as the energy source, the motional induction of salt ions moving through the earth's magnetic field, that generates an electromotive force that creates electric fields (E), which in turn drive electric currents (J) in the water column. The observed electric field was converted (Sanford 1971) to vertically-averaged horizontal velocity. Two adjustments of the observations were made. First, H3 was replaced with H5, padding H4 observations for the missing observations from Jun to Dec '12 with the value 3.1 Sv (the average Dec '12 to Jun '13), and making the adjustment based on the covariances of the baroclinic values of electrical conductivity and velocity (from Vigan et al. GEM model based on the PIES component of the HPIES).

The various transport estimates are denoted in the upper portion of the top panel in Fig. 9. The transports are computed from integrals of velocity over the observed vertical and horizontal sampling intervals. The mooring data are over 50–450 m, extrapolated to the surface and 600 m. The HEF values are over the total water depth. The Seaglider transports are over the upper 1,000 m. The observations are integrated over the same lateral distance.

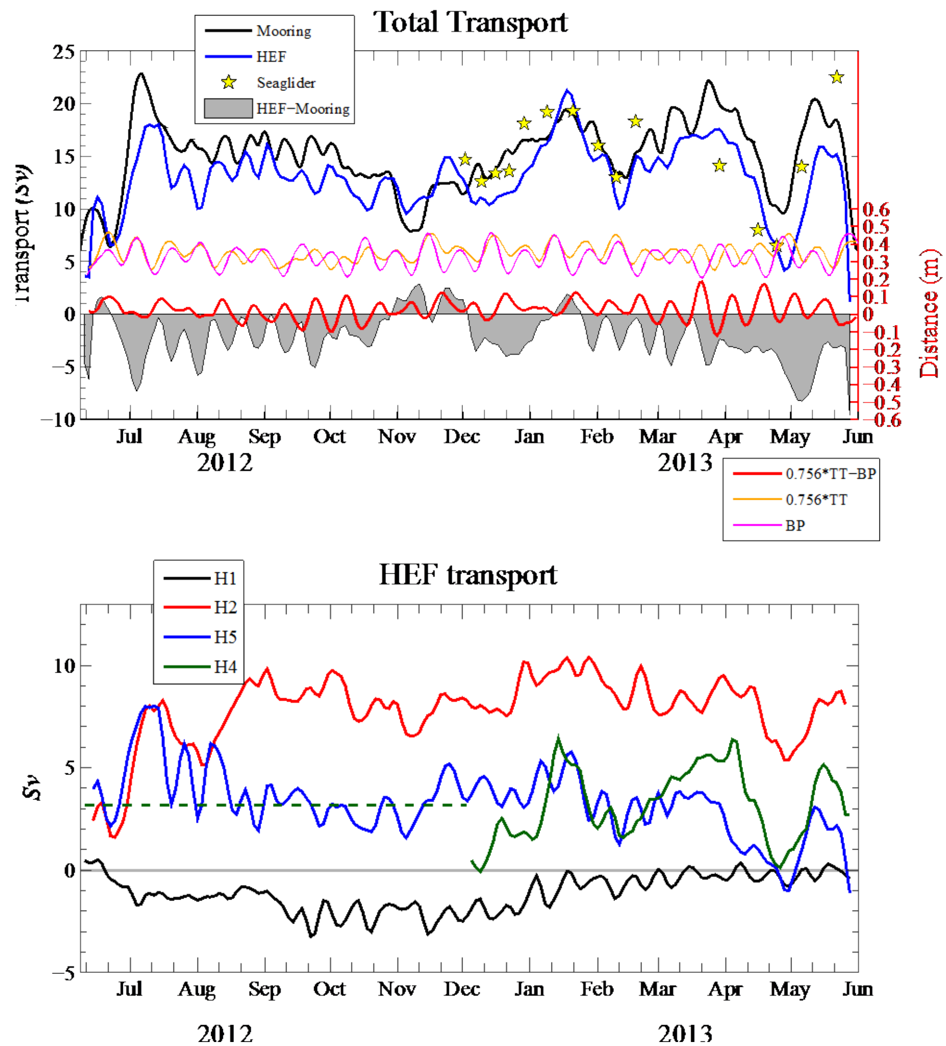

Fig. 9: Upper panel shows north–south transports from HEF/PIES and comparisons with ADCP mooring and Seaglider observations. The difference between HEF and mooring transport estimates is shown in grey fill. The lower panel shows the observed N–S volume transports for the four HPIES.

The difference between the HEF and mooring transport estimates are displayed in the upper panel (gray fill). It is significant that the difference is 2–3 Sv, which is about what is thought to be the amount of the Kuroshio Undercurrent. Much of this undercurrent is contributed by the H1 site, consistent with the PIES measurements (Fig. 8). The strong biweekly variability is clearly the amplitude of the spring–neap tidal transport. The barotropic tide is the same in mooring and HEF velocity observations, so the difference shown is caused by the baroclinic component (i.e., internal tide). Both results of volume transport and tidal flows support the credibility of the HPIES observations.

It is gratifying that the various transport values converge nicely and the very similar major fluctuations are seen in all three methods. It is clear that the utility of the combination of full water column measurements from HEF and PIES are nicely supported by the comparisons.

The spring–neap variations in transport are contributed by the baroclinic tidal flow. The thin lines are the IES travel time (TT) variations converted to depth variations and bottom pressure variations (BP). The difference is the thick red curve, which has the surface height effect removed and may be the internal tide. A current project is to determine which effect, BP or TT, is larger for a low mode internal wave. That is, are temperature changes in TT more responsible compared to the BP changes from the density variations?

IMPACT/APPLICATIONS

Two new instrument systems demonstrated their scientific utility in OKMC. First, the EM-APEX determined vertical and horizontal structure of the NEC and where it bifurcated into the Mindanao and Kuroshio currents. Second, the ability to observe the transport of major currents by HPIES, a single instrument that observes the electric field and acoustic travel time from the seafloor, is a major advance. Both of these technologies have the potential to increase our observations and understandings of ocean currents and planetary waves.

TRANSITIONS

Two HPIES are now operating on the NSF OOI cable array off the Pacific NW coast. The records are now over one year long. In addition, EM-APEX floats are being used in multiple experiments, especially recently in the ACC and being considered for some naval or DARPA applied programs.

RELATED PROJECTS

Quantify Lateral Dispersion and Turbulent Mixing by Spatial Array of χ-EM-APEX Floats **(**N00014-09-1-0193) as part of the LatMix DRI. A suite of twenty-one EM-APEX floats, 10 with χ turbulence sensors, was used in three experiments SE of Cape Hatteras, NC in June 2011. This was the first time a number of EM-APEX has been choreographed to profile simultaneously. For most of the time, the RMS differences on arrival at the surface as less than 1 minute. Only a single float was lost during the experiment, a result that partly was achieved by the development and use of a situation awareness system developed at APL-UW for this experiment. Assets in the water were displayed on a dedicated screen on the bridge of each of the three research vessels. More than 8,000 CTD and velocity profiles were obtained in the three experiments. Preliminary results were presented at the *Ocean Sciences Meeting* in February 2014.

PUBLICATIONS

Andres, M., S. Jan, T.B. Sanford, V. Mensah, L. Centurioni, and J. Book, 2015: A new look at the low-latitude Western Pacific. *Oceanography* (submitted)

Tsai, C.-J., M. Andres, S. Jan, V. Mensah, T. B. Sanford, R.-C. Lien, and C. M. Lee, 2015: Eddy-Kuroshio interaction processes revealed by mooring observations off Taiwan and Luzon. *J. Geophys. Res.* (accepted)

Lien, R.-C., B. Ma, C. Lee, T. B. Sanford, V. Mensah, L. R. Centurioni, B. D. Cornuelle, G. Gopalakrishnan, J. L. McClean, A. L. Gordon, M.-H. Chang, S. R. Jayne, and Y.-J. Yang, 2015: The Kuroshio and Luzon Undercurrent east of Luzon Island, *Oceanography* (submitted)

Mensah, V., M. Andres, B. Ma, and R.-C. Lien, 2014: Optimization of PIES data processing: Comparison with Seaglider and ADCP mooring data. (Unpublished note)

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